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Computational Study of Flow Establishment in Hypersonic Pulse Facilities

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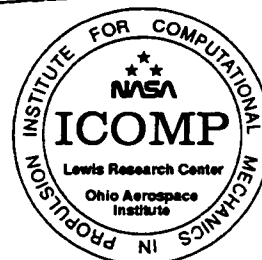
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COMPUTATIONAL STUDY OF FLOW ESTABLISHMENT IN HYPERSONIC PULSE FACILITIES

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ABSTRACT

This paper presents a study of the temporal evolution of the combustion flowfield established by the interaction of ram-accelerator-type projectiles with an explosive gas mixture accelerated to hypersonic speeds in an expansion tube. The Navier-Stokes equations for a chemically reacting gas are solved in a fully coupled manner using an implicit, time accurate algorithm. The solution procedure is based on a spatially second order, total variation diminishing (TVD) scheme and a temporally second order, variable-step, backward differentiation formula method. The hydrogen-oxygen chemistry is modeled with a 9-species, 19-step mechanism. The accuracy of the solution method is first demonstrated by several benchmark calculations. Numerical simulations of expansion tube flowfields are then presented for two different configurations. In particular, the development of the shock-induced combustion process is followed. In one case, designed to ensure ignition only in the boundary layer, the lateral extent of the combustion front during the initial transient phase was surprisingly large. The time histories of the calculated thrust and drag forces on the ram accelerator projectile are also presented.

INTRODUCTION

A major difficulty associated with ground testing of hypersonic propulsion systems in pulse facilities is the short test time available (on the order of a millisecond). In some cases, the test time may be less than the time required to fully establish the reacting flow, especially if recirculation zones and shock wave/boundary layer or detonation wave/boundary layer interactions are present. Numerical simulation of the temporal evolution of the combustion process can supplement experimental work by providing detailed information about reaction initiation and flow establishment time in pulse facilities.

In this paper we investigate numerically the combustion process generated by the interaction between an axisymmetric projectile and an explosive gas mixture that has been accelerated to hypersonic speeds in an expansion tube. The principal advantage of the expansion tube over the shock tube or shock tunnel for this type of flow is that its operating cycle does not involve stagnation of the test gas. Therefore, with proper care, explosive mixtures can be accelerated to superdetonative velocities without autoignition, as demonstrated by Srulijes et al [1] in their experimental investigation of ram

accelerator [2,3] flowfields. In fact, ram accelerator type flowfields can be studied more easily in a fixed projectile, moving gas frame of reference than in the ram accelerator itself, where measurements are difficult to make.

However, important differences exist between the ram accelerator and an expansion tube experiment in the boundary layer growth along walls and flow characteristics during startup. Specifically, in the expansion tube the test time begins after passage of the shock wave and contact discontinuity over the projectile, as described below. On the other hand, startup in the ram accelerator follows the bursting of the first diaphragm by the projectile, a process that generates shock and expansion waves. In addition, the high fill pressures typical of ram accelerator operation cannot be duplicated in an expansion tube. The effects of these differences can be examined by using CFD methods.

An expansion tube consists of a single tube divided into three or four sections by diaphragms, as shown in Figure 1, which is a schematic of the classic expansion tube described by Trimp1 [4]. When the test gas consists of an explosive mixture, a buffer zone containing an inert gas is added between the test gas and the driver gas to prevent autoignition following rupture of the primary diaphragm [1].

A brief explanation of the operation of the expansion tube is necessary in order to clarify the assumptions made in the numerical simulations. Following the rupture of the primary diaphragm at time $t = 0$ (see Fig. 1), a primary shock wave propagates into the test gas and an expansion wave into the driver gas. The numbering of the flow states in Fig. 1 corresponds to that defined by Trimp1 [4]. On reaching the end of the driven section, the primary shock ruptures the secondary diaphragm and a secondary shock wave propagates into the expansion section, while an expansion wave moves into the test gas. This expansion wave is washed downstream, since the gas in region 2 is moving at supersonic speeds. Test time begins with the passage of the test gas/accelerating gas contact discontinuity over the model and ends with the arrival of the expansion wave. The state of the gas in region 5 determines the test conditions. Test times in expansion tubes are typically tens to hundreds of microseconds long [5]. An advantage of CFD analysis is that the test time can be extended arbitrarily, in order to estimate the flow establishment time.

Previous computational studies by Jacobs [5] and Wilson [6] simulated the flow of nonexplosive mixtures inside the expansion tube for the time interval $0 \leq t \leq t_2$ (see Fig. 1). In contrast, the goal of the present work was to examine the establishment of the flow of an explosive mixture over the test model. Therefore, our simulations were performed for times $t \geq t_2$.

NUMERICAL FORMULATION

Governing Equations

The conservation form of the nonequilibrium Navier-Stokes equations describing two-dimensional or axisymmetric chemically reacting flow involving n species can be written in general curvilinear coordinates (ξ, η) as follows:

$$\frac{\partial Q}{\partial t} + \frac{\partial (F - F_v)}{\partial \xi} + \frac{\partial (G - G_v)}{\partial \eta} + J (S - S_v) = W \quad (1)$$

where the parameter J is zero for two-dimensional flow and one for axisymmetric flow and Q is the vector of dependent variables:

$$Q = J^{-1} [\rho_1, \rho_2, \dots, \rho_n, \rho u, \rho v, e]^T \quad (2)$$

The dependent variables are the mass density of the i th species ρ_i , the velocity components u and v , and the total energy per unit volume e . J is the grid Jacobian and F and G are the inviscid flux vectors in the ξ and η directions, respectively. F_v and G_v are analogous viscous fluxes. S and S_v are axisymmetric source terms and W is the chemical source term. A detailed description of the terms in Eq. (1) and additional state and constitutive equations needed for system closure are given by Yungster [7].

Numerical Method

The numerical method used for solving Eq. 1 is described in detail in Ref. [8] and summarized briefly here. For simplicity, only the two-dimensional Euler equations are considered in this description; however, extension to the viscous case is straightforward [8]. The equation set is discretized using a temporally second-order, variable-step backward differentiation formula (BDF) method, which can be written as:

$$\Delta Q_{j,k}^n = \gamma \Delta Q_{j,k}^{n-1} - \beta \Delta t^n [\tilde{F}_{j+1/2,k} - \tilde{F}_{j-1/2,k} + \tilde{G}_{j,k+1/2} - \tilde{G}_{j,k-1/2} - W_{j,k}]^{n+1} \quad (3)$$

$$\Delta Q_{j,k}^n = Q_{j,k}^{n+1} - Q_{j,k}^n \quad (4)$$

where γ and β are variable-step BDF method coefficients [8], and Δt^n is the time step. The terms $\tilde{F}$ and $\tilde{G}$ are the numerical fluxes in the ξ and η directions. They are computed using Yee's second order total variation diminishing (TVD) scheme [9]. Equation 3 is then linearized in a conservative manner and solved iteratively, using a lower-upper relaxation procedure consisting of successive Gauss-Seidel (LU-SGS) sweeps. At each time step the iterative process of producing successively improved approximate solutions to equation (3) is continued until a suitable convergence criterion is satisfied. The inversion of large matrices is avoided by partitioning the system into reacting and non-reacting parts; however, a fully coupled interaction is still maintained. Consequently, the matrices that have to be inverted are of the same size as those that arise in the commonly used point implicit methods. An important advantage of the present method is that it remains stable for large values of the CFL number, so that large time steps can be used.

RESULTS

Benchmark test cases

Before applying the present method to the study of expansion tube reacting flows, its accuracy was first established by computing various benchmark test cases. Two such cases are presented below for reacting and nonreacting, inviscid flows.

The first case was a simulation of Lehr's ballistic range experiments [10], which consisted of spherical nosed projectiles of diameter 15-mm being fired into a premixed, stoichiometric hydrogen-air mixture. Figure 2a shows a shadowgraph image obtained by Lehr [10] for a Mach number $M = 4.79$. The corresponding computational result, obtained with a 9-species, 19-step reaction mechanism for hydrogen-oxygen [8], is shown in Fig. 2b in the form of density contours. Under the conditions of the test, the reacting flow was unstable, resulting in a highly regular, periodic flow structure. An experimental oscillation frequency of 720 kHz was reported [10]. The computed frequency of oscillation varied from 701 to 716 kHz. Computations of other flow conditions also produced excellent agreement with experimental data [8].

The second test case was the regular reflection of an incident shock wave from a 55° wedge. Experiments were conducted in a 60 mm x 150 mm shock tube at the Institute of Fluid Science of Tohoku University and results reported by Falcovitz et al [11], who also performed numerical simulations for several cases. Figure 3 gives their experimental holographic interferograms and our computed density contours at three different times during the reflection process for an incident shock Mach number of 1.488. The spacing of the contours was selected to match that observed in the experimental interferograms. The computational results were generated with a 400 x 316 uniform grid. Figures 3a and 3b show the reflected shock wave prior to its collision with the shock tube end-wall. Figures 3b to 3g show the wave configuration at two different times after collision with the end-wall. It should be pointed out that due to a small air gap between the end wall of the shock tube and its upper wall an expansion wave was generated at the upper edge of the end-wall [11]. This expansion wave can be observed in Fig. 3c near the upper right corner of the holographic interferogram and in Fig. 3e near one of the reflected shocks. The air gap was not modeled in our computations.

The agreement between the computational and experimental results is excellent at all times. The computations match almost every fringe in the experiments, except immediately after the head-on collision near the right corner (Fig. 3d), where the grid is not fine enough to resolve the details of the reflection. The overall resolution of the flowfield compared well with the numerical results computed by Falcovitz et al [11]. However, near the walls the present method produced superior results. Note especially that the small, closed fringe near the bottom corner was reproduced in our calculation (Figs. 3d and 3g), whereas it was not captured by Falcovitz et al.

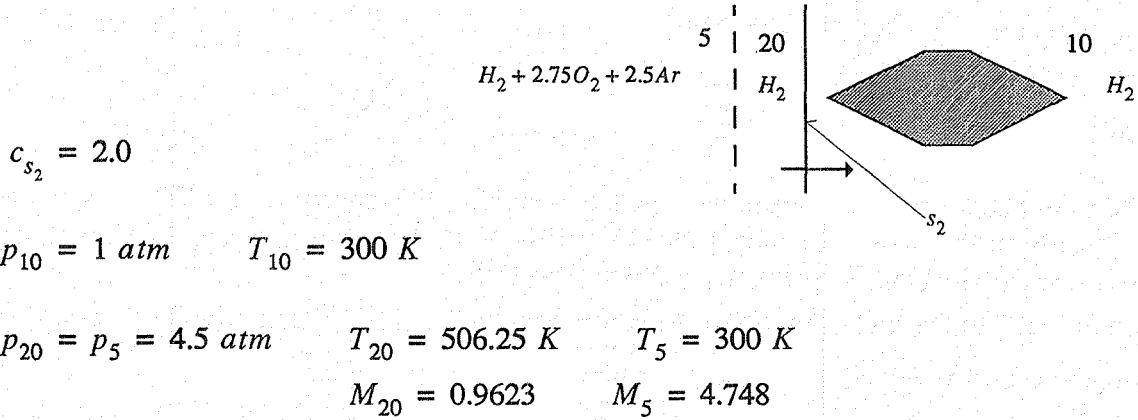
Expansion tube reacting flows

Two cases are presented, the first involving only boundary layer ignition, and the second a ram accelerator type configuration. Both cases employed pure hydrogen as the accelerating gas and the mixture $H_2 + 2.75O_2 + 2.5Ar$ as the test gas. The $H_2 - O_2$ reaction mechanism consisted of 19 reac-

tions among 9 species [8].

Case 1

This case considered an axisymmetric projectile composed of two 30° half angle cones and a short straight section. The corners of the projectile were rounded. The projectile overall length and maximum diameter were 1.45 cm and 0.693 cm, respectively. The flow conditions for this test are shown in the schematic below:



Here c denotes the shock speed and p , T and M are the pressure, temperature and Mach number, respectively. The conditions for this case were selected to produce ignition in the boundary layer. The flow was assumed to be laminar and the projectile surface adiabatic. A 320x110 nonuniform grid was utilized. The time evolution of the flowfield is shown in Fig. 4 by means of nondimensional temperature (T/T_{10}) contours. In Fig. 4a the secondary shock has just reached the tip of the projectile. The shock is partly reflected from the projectile surface and continues to travel downstream. The reflection is too weak for the temperature range used and is therefore not apparent in Fig. 4. As the high Mach number test gas reaches the projectile (Fig. 4b), a conical shock begins to form over its nose. A short time later (Fig. 4c), combustion begins in the boundary layer. Subsequently, the reacting boundary layer penetrates region 20 of the accelerating gas. Once the reacting gas reaches the projectile shoulder, its lateral expansion is considerable. The penetration of the reacting boundary layer can be explained by the fact that as the conical shock begins to form over the nose of the projectile, a large pressure is established over this region. The shock has not yet formed downstream, thereby creating a substantial pressure gradient, which forces the boundary layer gases downstream. After the transient phase, combustion is observed only along the boundary layer (Fig. 4i), which separates over the rear of the projectile. The computation was stopped at $t = 13.52 \mu\text{sec}$, although the flow had not yet reached steady state. This simulation required 6200 iterations and 12.4 hrs. of CPU time on a Cray C90 computer, with a maximum CFL number of between 3 and 10.

Case 2

This case considered a ram accelerator configuration that included an axisymmetric projectile and a ram accelerator tube. As shown in Fig. 5a, the front end of the tube was positioned slightly behind

the projectile shoulder, in order to limit the boundary layer growth and thus simulate conditions in the actual ram accelerator. The projectile comprised a 15° half angle nose cone, a 30° axisymmetric ramp, a constant diameter section and a specially configured tail. The total length of the projectile, its maximum diameter and the ram accelerator tube diameter were 10.85 cm, 2.82 cm and 3.8 cm, respectively. These dimensions are based on the experimental device currently operating at the University of Washington [2,3]. The flow conditions for this test case were

$$c_{s_2} = 2.35$$

$$p_{10} = 1 \text{ atm} \quad T_{10} = T_5 = 300 \text{ K} \quad T_{20} = 597.93 \text{ K}$$

$$p_{20} = p_5 = 6.276 \text{ atm} \quad M_{20} = 1.136 \quad M_5 = 6.058$$

The flow was assumed to be turbulent, and a constant wall temperature of 300 K was specified at the projectile surface and at the tube wall. The Baldwin-Lomax turbulence model [12] was used in this calculation. A 315x125 nonuniform grid was utilized. The time evolution of the flowfield is shown in Fig. 5 in the form of nondimensional temperature (T/T_{10}) contours (bottom half of each figure) and pressure (p/p_{10}) contours (top half). Note that for clarity in presentation the pressure and temperature contour ranges are not the same for all the plots. Each color bar defines the contour range both for the figure in which it appears and for every subsequent plot until a new color bar appears.

The initial flow development for this case is similar to that described for the previous one. That is, the flow begins with the arrival of the secondary shock (Fig. 5a), its reflection off the projectile (Fig. 5b) and the formation of the conical shock over its nose (Fig. 5c). At subsequent times, the secondary shock is reflected off the projectile's ramp (Fig. 5d) and a series of wave reflections from the tube wall and projectile surface can be observed in Figs. 5e and 5f. The conical shock reflected off the tube wall begins to establish in Fig. 5g and shortly after it hits the projectile surface ignition occurs in the boundary layer (Fig. 5h). Combustion spreads both downstream and towards the tube wall and, at the same time, propagates upstream through the boundary layer (Fig. 5i-k). A shock-induced combustion wave is established, creating a large pressure over the back of the projectile, and positive thrust begins to be generated at $t = 68 \mu\text{sec}$ approximately. The combustion continues to propagate upstream along the projectile boundary layer and also along the tube wall boundary layer (Fig. 5l-n), until unstart occurs (Fig. 5o). For this calculation the maximum CFL number varied between 5 and 15. The computational work requirement was 7000 iterations and 11.3 hrs. on a Cray C90 computer.

The total thrust and viscous drag forces on the projectile are plotted in Fig. 6. During flow initiation, the projectile is subjected to an increasing drag force, as the conical wave system is established over the projectile. When combustion begins, a progressive reduction in total drag is observed, but positive thrust is produced only after the shock-induced combustion wave is reflected off the projectile surface, resulting in the steep increase in total thrust shown in Fig. 6. The viscous drag builds up in a similar manner and decreases significantly once the combustion process starts. Note that the viscous drag accounts for less than 1% of the total thrust.

CONCLUSIONS

The expansion tube is a useful tool for investigating ram-accelerator-type phenomena. However, important issues such as boundary layer growth along walls, startup characteristics and operating pressures will prevent the expansion tube from duplicating exactly the conditions in a ram accelerator. In addition, the short test time available may be insufficient to establish fully the reacting flow-field. Computational studies can support experimental efforts by providing answers to these issues. A methodology for simulating the combustion process in expansion tube flowfields was described, and computations for two cases were presented to illustrate the capability of the numerical approach. The unexpected combustion phenomenon observed during the initial transient phase emphasizes the need for further study of this type of flow. The efficiency of our time-accurate, fully implicit numerical method was demonstrated by computing high-speed, reacting, turbulent flows at CFL numbers as high as 15.

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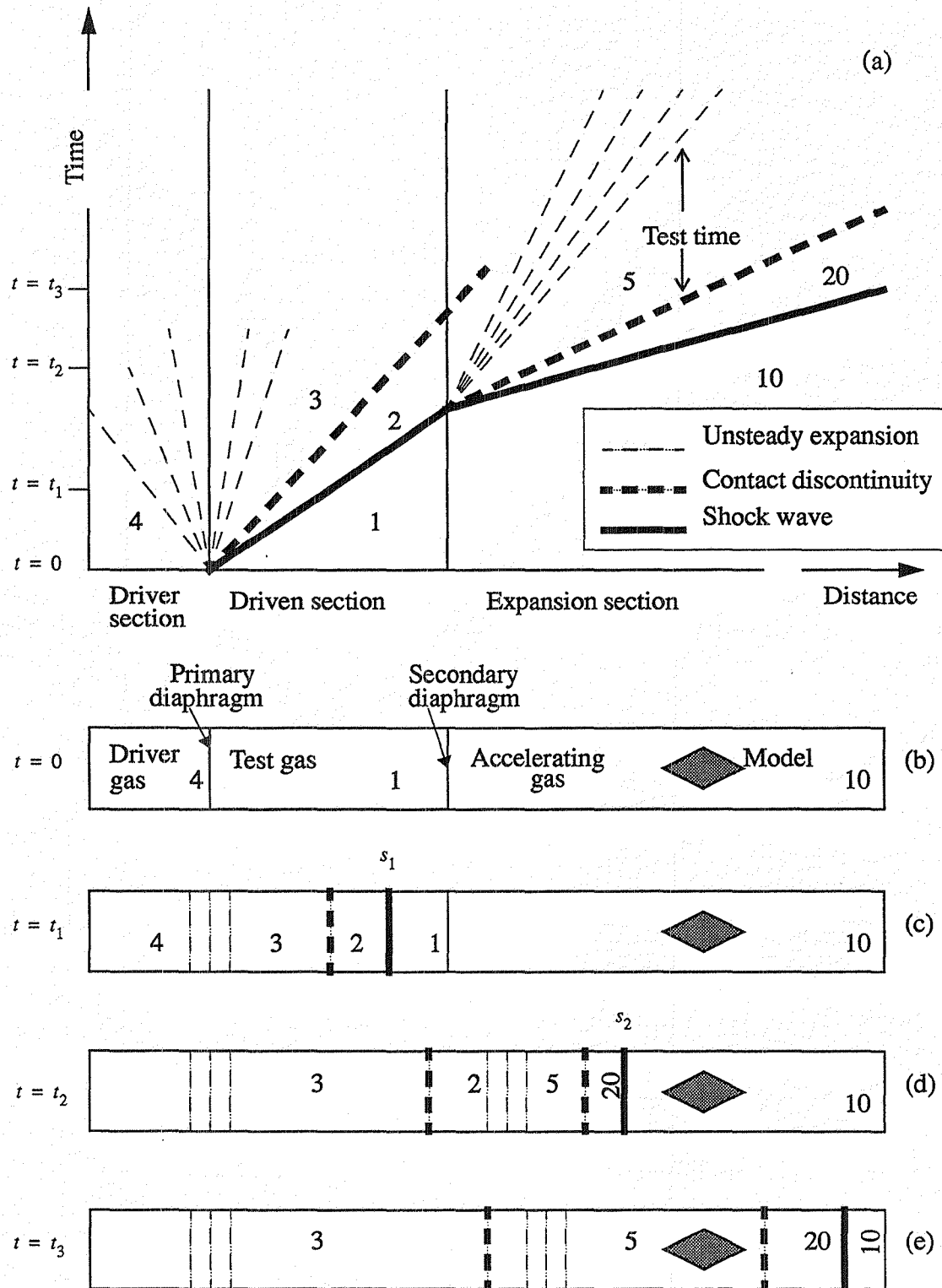
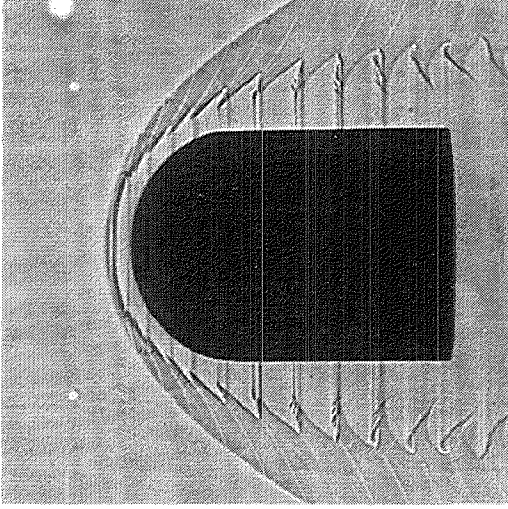
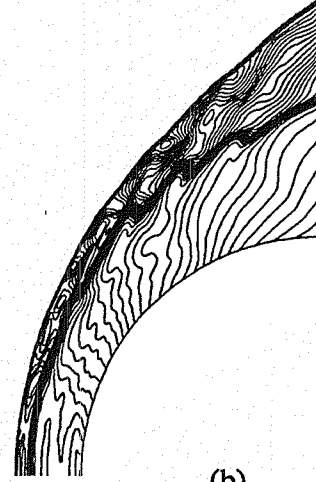


Figure 1. Schematic of the expansion tube cycle. The numbers identify the various flow regions as defined by Trimpi [4].

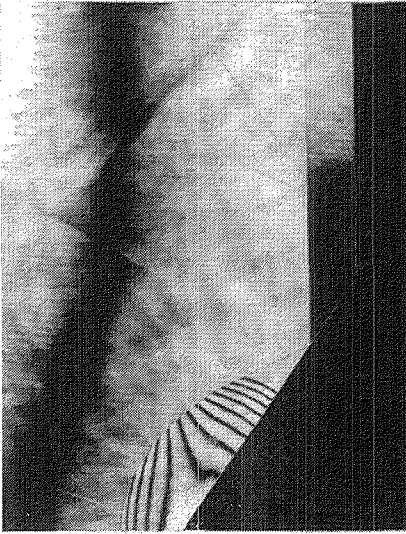


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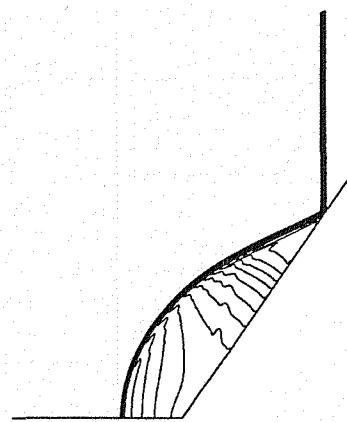


(b)

Figure 2. Experimental and computational results for a projectile moving at $M = 4.79$ in a stoichiometric hydrogen-air mixture: (a) experimental shadowgraph image (Lehr [10]); (b) density contours.

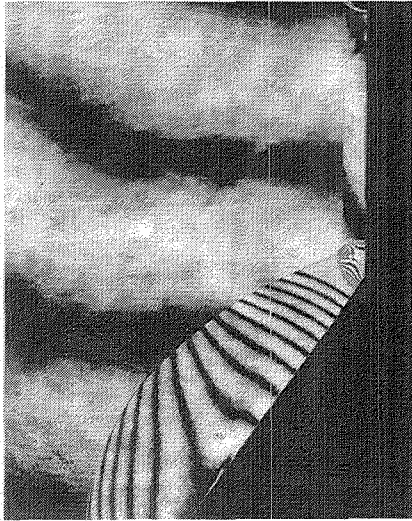


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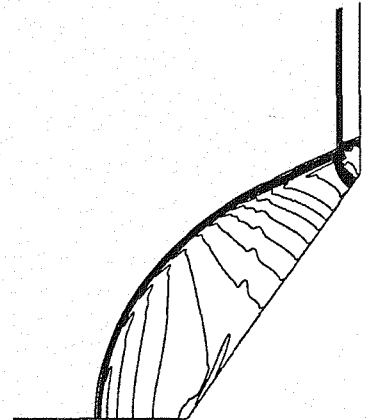


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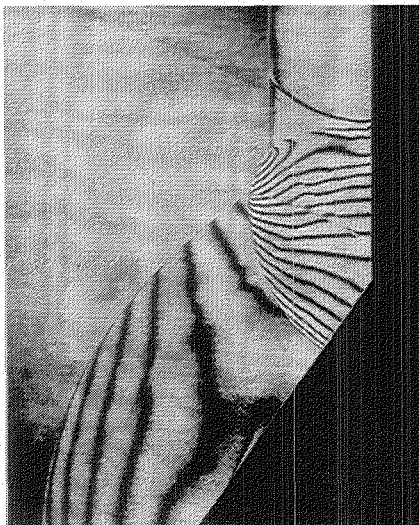
Figure 3. Temporal evolution of the regular reflection of a $M = 1.488$ shock wave with a $\theta = 55^\circ$ wedge. (a) Holographic interferogram prior to its interaction with the end wall [11]; (b) computed density contours.



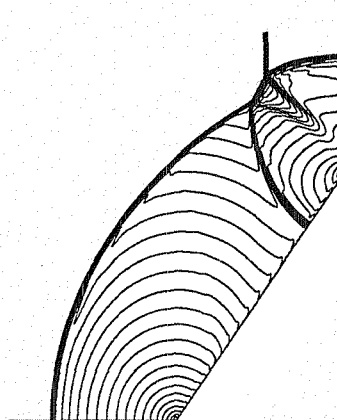
(c)



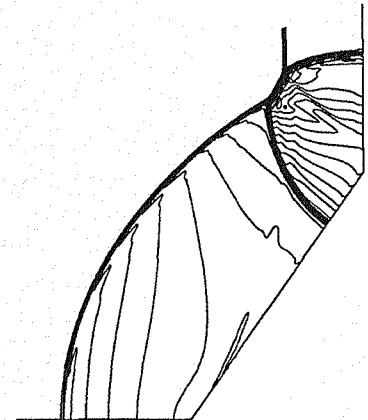
(d)



(e)



(f)



(g)

Figure 3 continued. (c), (e) Holographic interferograms at two time intervals after collision with the shock tube end-wall [11]; (d), (g) computed density contours; (f) computed Mach number contours.

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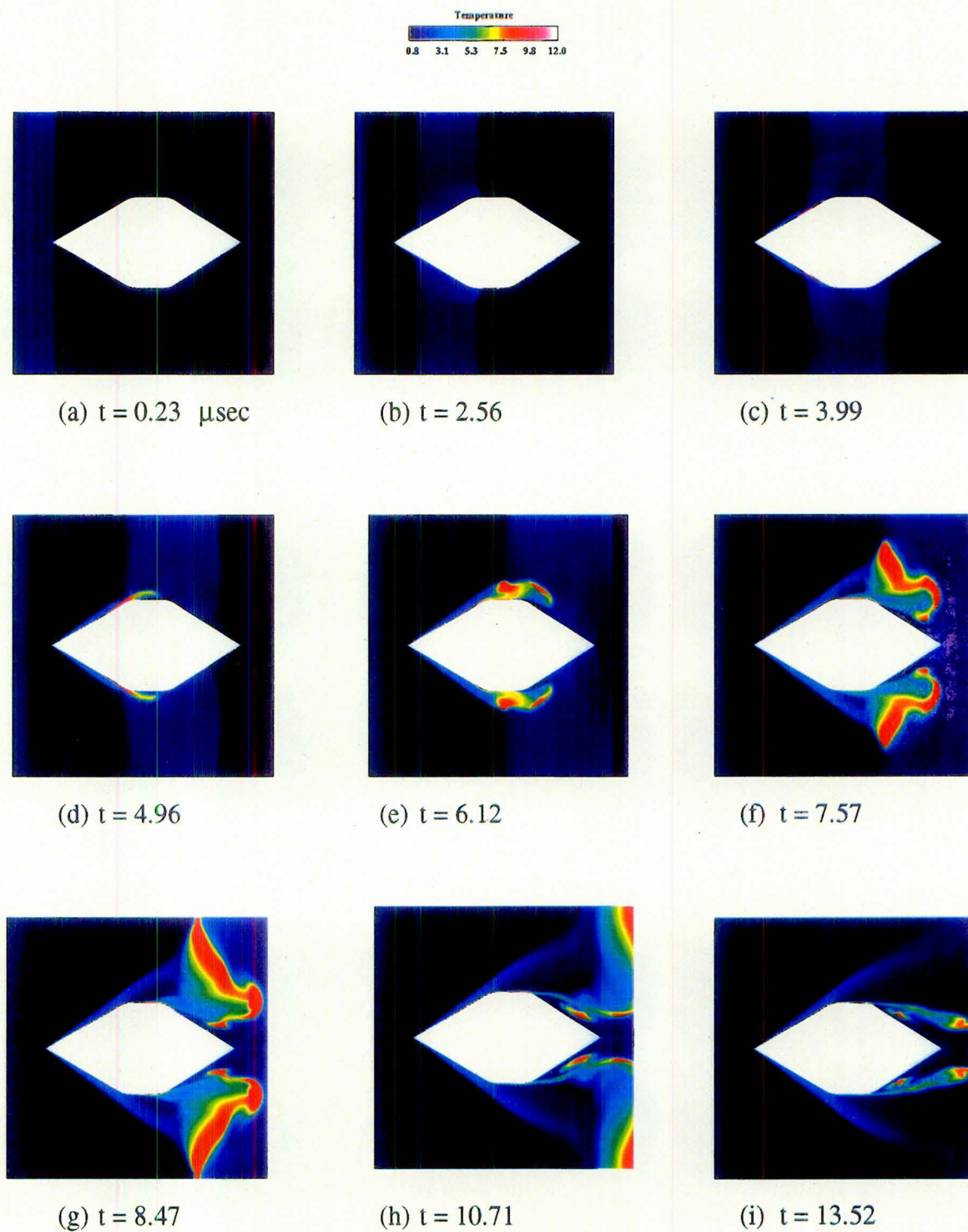


Figure 4. Nondimensional temperature contours T/T_{10} showing temporal evolution of expansion tube flow over an axisymmetric projectile. Test gas: $H_2 + 2.75O_2 + 2.5Ar$.

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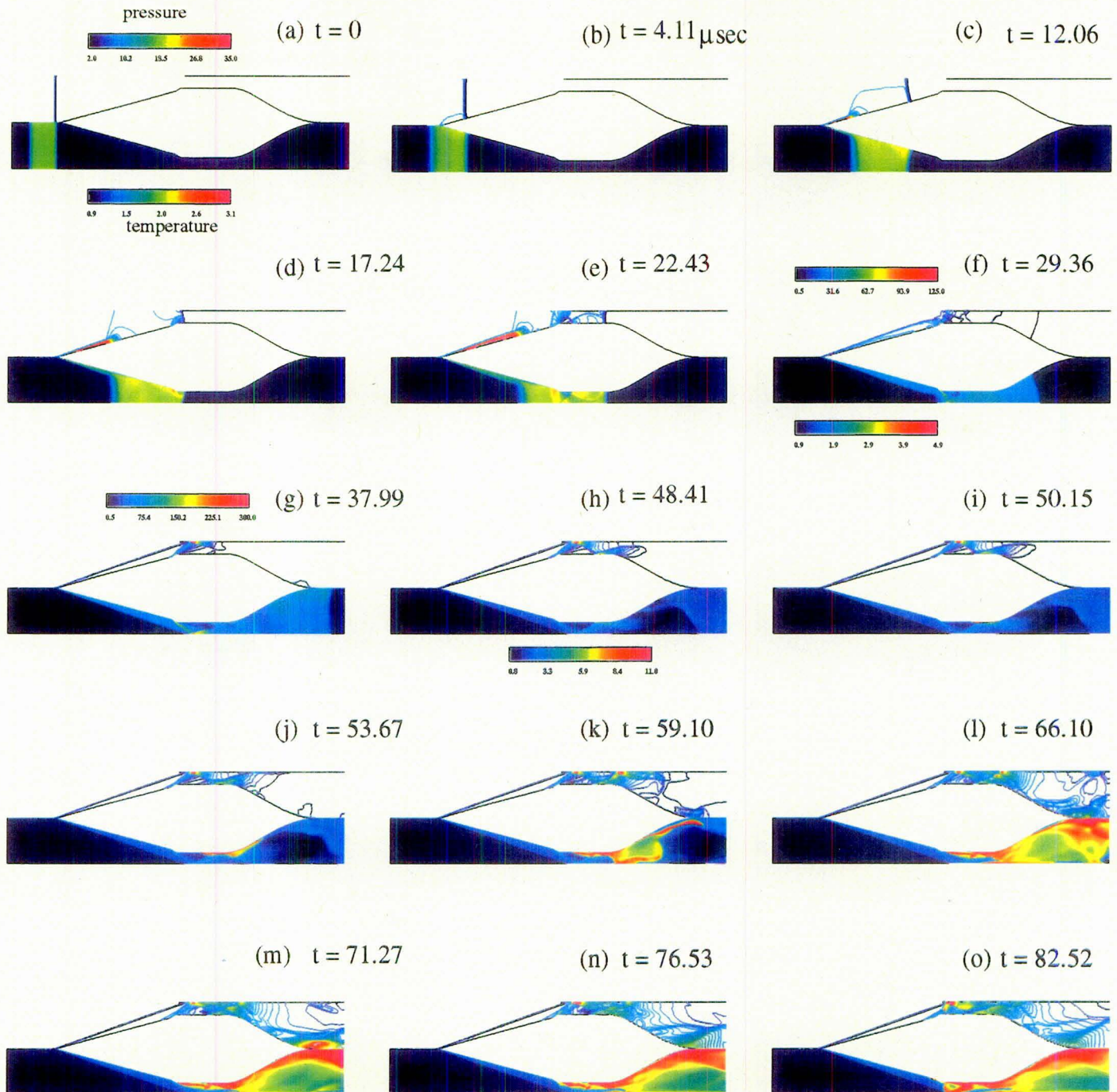


Figure 5. Nondimensional pressure (p/p_{10} , top half) and temperature (T/T_{10} , bottom half) showing temporal evolution of expansion tube flow over a ram accelerator configuration. Test gas: $H_2 + 2.75O_2 + 2.5Ar$. Note: color bar defines contour range both for the plot in which it appears and for every subsequent plot until a new color bar appears.

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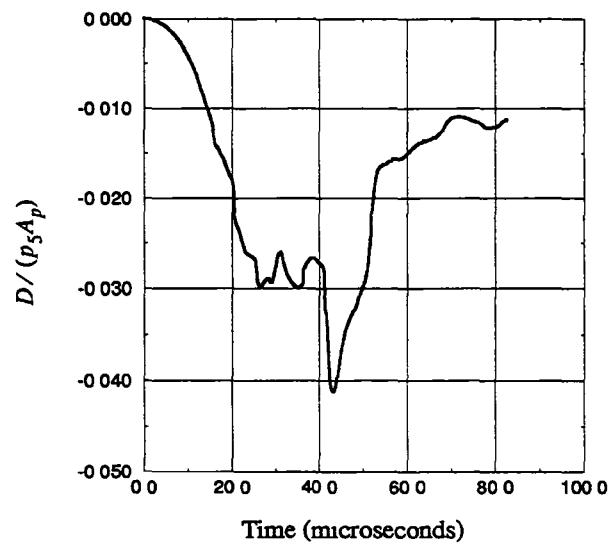
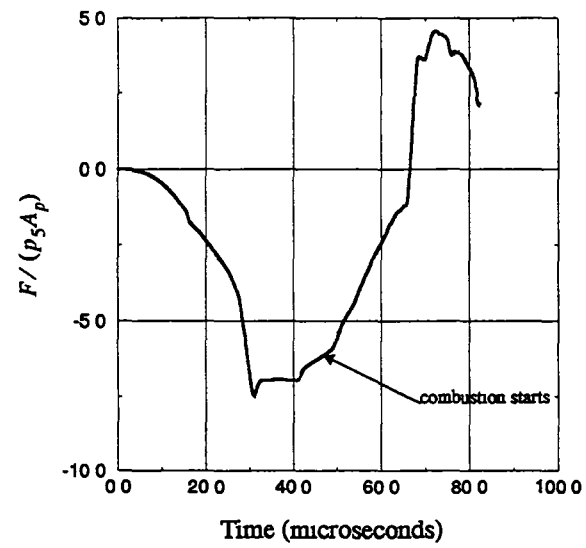


Figure 6. Nondimensional net thrust (a) and viscous drag (b) forces on ram accelerator projectile. (Here, A_p is the maximum cross-sectional area of the projectile).

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